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A Summary of the Results from the

UCLA OGO-5 Fluxgate Magnetometer

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16. Abstract

The UCLA OGO-5 fluxgate magnetometer experiment (E-14) was designed to measure the vector magnetic field over the full range of the OGO-5 orbit. Thus, it had a dynamic range of $\pm 64,000\gamma$ yet it maintained a precision of $\pm 1/16\gamma$ at all times. This enabled a broad spectrum of problems to be attached. Studies of the magnetospheric waves, currents, waves-particle interactions, pitch angle distributions and wave normal directions were made. The structure of the magnetopause the magnetotail and bow shock were probed, waves and discontinuities in the solar wind were examined and the various phases of substorms were examined in depth. These studies resulted in our 140 papers published and presented at scientific meetings during the contract period using the magnetic field data.

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Preface

The objective of the UCLA OGO-5 fluxgate magnetometer experiment (Experiment E-14) was to measure the magnitude and variations of the vector magnetic field over the complete orbit of the satellite. This permitted the study of a wide range of phenomena: magnetospheric waves and currents, structure, waves and discontinuities in the interplanetary medium, and the variations in the tail accompanying substorms. The magnetometer was sensitive to fluctuations as small as $\pm$ 1/6γ even in background fields as large as 64,000γ and thus revealed a variety of phenomena previously unobserved. At the same time it provided pitch angle data for the OGO-5 particle experiments.

The analysis of this data has resulted in over 140 papers both written and oral. Only a brief summary of these results is possible here. This set of data has proved so bountiful that the analysis to date is far from complete despite the intensive work to date. It is expected that new and significant results will continue to be obtained from these data as long as meaningful levels of funding are provided.

Table of Contents

1. Introduction

Studies of the data from the UCLA OGO-5 fluxgate magnetometer have contributed greatly to the understanding of the geomagnetic cavity, which includes the magnetotail and polar cusp as well as the magnetosphere proper; the magnetospheric boundary regions, the magnetopause, magnetosheath and shock front; and the interplanetary medium. The value of the data results from the characteristics of the instrument: wide dynamic range, high sensitivity, and linearity; from the nearly-continuous data acquisition, from the high data rates provided by the OGO-5 spacecraft; and finally from the willingness of the OGO-5 experimenters to participate in data exchange at a relatively early stage in the data analysis. At this time, there are 60 papers, published or submitted for publication, in which the UCLA OGO-5 fluxgate data made a significant contribution. As a result of the policy of relatively free data exchange, 40 of these contained data from more than one OGO-5 instrument. The UCLA OGO-5 fluxgate data have also been utilized in some 74 papers presented at scientific meetings, and one Ph.D. dissertation has been based, in part, on these data.

2. Instrumentation

The sensor consists of three mutually orthogonal fluxgate probes mounted on the outboard section of the EP-5 boom. The electronics package for the experiment is mounted on the +Z door. The basic magnetometer measures the field between $\pm 16\gamma$ in $1/8\gamma$ steps. When the field is beyond this range, external fields are applied to the sensor to return the basic magnetometer reading to a value in the range $\pm 16\gamma$. There are 64 16 gamma steps which provide a range of $\pm 512\gamma$. When the magnetic field exceeds this range external fields are added in 1024γ steps. There are 128 such steps giving a total dynamic range of $\pm 64{,}000\gamma$ while maintaining a precision of $\pm 1/16\gamma$ at all times.

The sensor has been described more fully in engineering papers[1, 2] and in the scientific literature.[84]

3. Data Processing

Our philosophy on data processing is to pass all the data through a program that produces a summary of the data with sufficient detail to distinguish and classify events and regions of interest in the data. The summary consists

of microfilm plots, printouts, and digital tapes. The microfilm plots consist of one minute averages of the vector magnetic field in spacecraft coordinates, in solar magnetospheric coordinates and solar ecliptic coordinates; one minute averages of the rms deviations of the vector field in spacecraft coordinates, and 4.6 second averages of the vector field in spacecraft coordinates. Our printouts contain only the one minute averages. Digital tapes exist for all the data plotted. Positional data are also processed for all the data, as discussed above.

From this library of data and satellite position any section in the processed record is available for immediate reprocessing at higher time resolution if it is determined that such a section is interesting. Since most scientifically interesting regions or events can be identified from the magnetic field data, these summary plots have been invaluable to other experimenters as well.

With this in mind, we attempted to process all the data our budget would allow. At the present time we have processed over 300 orbits of magnetometer data. This brings the processing well into the third year of operation of OGO-5. This provided complete local time coverage but not complete coverage of all regions of space that OGO-5's orbit eventually will traverse since solar-lunar perturbations make each year's coverage slightly different. We presently have about one year's data remaining to be processed.

4. Submittal of Data to NSSDC

Presently NSSDC has microfilm copies of all the plots of the OGO-5 positional data. We have also provided NSSDC with microfilm plots of the first two years magnetometer data, and magnetic tapes of the first year's data. Further, we have supplied the National Space Science Data Center with microfilm plots of trajectory information for OGO-5. We have completed this project by supplying them with orbital plots for all 500 OGO-5 orbits for which trajectory tapes were produced. The NSSDC has in turn supplied these plots to other interested OGO-5 experimenters.

5. Data Exchange

We have provided two of the OGO-5 particle experimenters (T. Farley of UCLA and H. West of Livermore) with complete records from the magnetometer. These experimenters used the magnetometer data to determine the pitch angle distributions of the measured particles. We have provided the search coil magnetometer experimenters (E.J. Smith of JPL and R.E. Holzer of UCLA) with data, covering specified intervals, for use in determining the electron gyro frequency and the angle of propagation of signals relative to the magnetic field. Similarly, data were provided, on request, to the TRW electric field experimenters.

Requested data segments are supplied regularly to the Lockheed ion mass spectrometer group and the JPL solar wind experimenters, and we continued our data exchange with the Explorer 33 and 35 magnetometer experimenters at Ames Research Center. The success of this policy of free data exchange can be judged from the results discussed in the following sections.

6. Scientific Results

6.1 Magnetosphere

With the data from the UCLA OGO-5 magnetometer, band-limited micropulsations were identified in space for the first time.[3-5] These pulsations had been observed on the ground for many years, but their existence above the ionosphere was in doubt. A preliminary analysis of OGO-5 micropulsation data has been published[6] and correlations with simultaneous ATS-1 wave observations is underway.[7] Evidence for wave-wave interactions detected between the ULF and VLF ranges was also obtained.[8] In these interactions the amplitude of the VLF waves is modulated by waves with periods of approximately 20 sec. A review paper on the OGO-5 and ATS-1 micropulsation data has summarized these results.[9]

The magnetospheric field strength in the dawn hemisphere was mapped using the data of the first six months of operation[10] and compared with the observations of the ATS-1 magnetometer at 6.6 R_e[11]. With the plasma density measured with the Lockheed ion mass spectrometer and the field strength measured with this instrument, Alfven velocity profiles were computed in the dawn

hemisphere. The relationship between the Alfven velocity and the occurrence of ELF hiss and chorus was then examined.[10,12] It was found that ELF hiss occurs within the plasmasphere when the Alfven velocity is about 500 km/sec and ELF chorus occurs in the outer magnetosphere when the Alfven velocity is below about 3000 km/sec. A study of wave-particle interactions in detached plasma regions outside the plasmasphere has been initiated.

Accurate measurements of the pitch angles of energetic protons and electrons were made for the first time in many regions of space[14-23, 39-41] with data provided by this magnetometer. Further, the data were used with those from the triaxial search coil magnetometer to determine the direction of propagation of ELF chorus and ELF hiss.[24-30]

The magnetic field data were used extensively by both the TRW VLF electric field experimenters and the UCLA-JPL search coil magnetometer experimenters to scale their data to the local electron gyrofrequencies (examples of such scaling are found in many papers such as[4, 31-34].

6.2 The Magnetotail and Substorms

During the past two years an extensive study of the magnetotail and substorms has been undertaken. This involved both surveys of the magnetic field data alone and correlative studies with other experimenters of individual events using simultaneous measurements of particles and fields. The first phase of the correlative study is now complete, resulting in a series of 9 papers to appear in the Journal of Geophysical Research.[35-43]

First, the magnetic field of the tail as observed with OGO-5 sometimes changes from the classical tail-like configuration to a nearly dipolar configuration at times of auroral zone magnetic activity.[44-46] Intercorrelations of the magnetic field on Explorer 33, 35, ATS-1, and OGO-5 indicate that the sourthward component of the interplanetary magnetic field causes changes in the tail preceding the onset of the expansion phase.[46-48] This period is called the growth phase. The signature of the expansion phase of a substorm in the distant magnetic field involves a return to a more dipolar field, and a decrease in the lobe field strength. This has been studied taking into account the solar dynamic pressure for a small number of

substorms[49] and without taking this into account for a much larger number of substorms.[50] Saito[51, 52] has shown that while OGO-5 was observing oscillations of the plasma sheet a pulsating Ps 6 substorm was in progress.

A comparison of OGO-5 and ATS-1 observations in the midnight meridian at the expansion phase onset showed that there is a compression of the field which moves radially inward.[53-56] Comparisons with data from the UCLA energetic electron detector revealed that, as the plasma sheet expanded during the substorm energetic particles appeared within the plasma sheet.[18, 39, 57, 58] During one substorm that was studied in detail the first direct evidence of betatron acceleration was obtained. This study has now been extended to many substorms.[59] We also found evidence that the ELF emissions are controlled by the size of the pitch angle anisotropy.[18,39] The pitch angle information provided with the magnetometer was also used to compare the changes in the fluxes of protons with the same pitch angle but different guiding centers. This study provided further evidence for the thinning of the plasma sheet while the satellite was still within the plasma sheet.[19, 21, 23, 41]

The picture of substorm phenomena that has emerged from these studies has been presented in several invited review papers at scientific conferences,[60-63] and has been prepared for publication.[64]

Studies of the ULF waves in the tail have revealed that the tail is quite quiet at these frequencies in the lobes. In the plasma sheet, a featureless f^{-2} spectrum of noise is observed during substorms. Otherwise the plasma sheet is quiet.[65-67] Field aligned currents have also been detected at the plasma sheet boundary of the same magnitude as those flowing in the auroral zones.[68-70] VLF electrostatic wave amplitudes are large at low altitudes in these currents implying in turn a large resistivity and parallel electric fields. Correlative studies of the plasma sheet morphology using both field and particle data have shown that the cross section of the plasma sheet is more rectangular than previously thought.[71-72]

6.3 The Polar Cusp

The possibility of direct entry of magnetosheath plasma into the auroral zone through the neutral points in the magnetosphere has been speculated for many years. Although in general this continuation of the neutral points

into the magnetosphere, the polar cusp, is at higher magnetic latitudes than the OGO-5 orbit, solar-lunar perturbations have increased the inclination of the OGO-5 orbit so that at disturbed times the orbit can intersect the polar cusp. This occurred during the outbound orbit of OGO-5 on November 1, 1968.[73-75] Data from this pass showed that magnetosheath electrons entered the magnetosphere directly; the field was extremely distorted and the polar cusp was extremely turbulent.[76] Ion cyclotron waves were observed[77] as well as electrostatic waves capable of producing moderate sized resistivities and thus potential drops along field lines.[78, 80] Comparisons with the interplanetary field measured on Explorer 33 showed that the location and properties of the cusp were controlled by the direction of the interplanetary magnetic field.[79,81]

6.4 The Magnetopause

The studies of the magnetic structure at the magnetopause show that the magnetopause is eroded when the interplanetary field is southward.[82,83] The eroded flux is carried back into the tail and apparently sets the stage for a substorm.[83] These studies also reveal that the magnetopause is constantly in motion and that the boundary motion includes oscillations that move from the nose of the magnetosphere towards the tail,[84] that this boundary motion is consistent with the Kelvin-Helmholtz instability;[84,85] and that the boundaries do not appear to be steady-state magnetohydrodynamic discontinuities.[84] Comparison of the magnetometer data with the JPL ion flux measurements show that at least on occasion the boundary can be resolved into an electron current portion and a proton current portion with a 1 to 4 ratio in thickness.[86]

Pitch angle information provided by the UCLA OGO-5 fluxgate magnetometer observations have allowed the detection of the asymmetries in the particle distributions at the magnetopause.[9]

6.5 The Magnetosheath

Fluxgate data were used in conjunction with data from the triaxial search coil magnetometer to determine the direction of propagation of ELF waves (lion roars) in the magnetosheath.[87,88] Comparison of field dips or nulls

observed in the magnetosheath with simultaneous VLF electric field data from the TRW experiment revealed strong electrostatic emissions correlated with these features thus suggesting current instabilities and merging.[89]

6.6 The Bow Shock

Measurements of the magnetic field and the solar wind flux taken as the spacecraft approaches the shock revealed a region of proton deceleration on the upstream edge of the shock.[90-92] Corresponding electron acceleration also occurs.[73] Simultaneous measurements with the Lockheed ion mass spectrometer have given the proton scattering and thermalization times.[94-98] The structure and role of dissipation in the bow shock was studied[89, 99-108] by comparing the shock's magnetic profile with the occurrence of VLF electric field noise. A similar comparison of the shock profiles with the ELF data of the search coil magnetometer revealed wave growth as the electrons are compressed across the shock front.[92, 93, 109-111] ULF waves were also studied at the shock.[112-117] These studies revealed that the precursor waves at the bow shock were not phase stationary as previously thought. Correlations of the shock structure with the theoretical predictions were also undertaken.[118, 119] The macroscopic structure and motion of the shock front were also studied.[120-123]

6.7 The Interplanetary Medium

Information on the presence of the earth's bow shock is transmitted well upstream from the shock into the interplanetary medium. At least part of the information propagates upstream as a hierarchy of waves. These waves were studied in detail using the UCLA OGO-5 fluxgate magnetometer data. At frequencies of about 0.4 Hz, the waves form discrete wave packets,[124] which are propagating toward the sun but are being blown backward toward the shock.[125, 126] These waves occur much more frequently on the dawn side of the shock than on the dusk side and appear to be attenuated with a scale length of about 4 R_e.[127,128] The SUI low energy proton experiment data revealed that these waves occur in the presence of upstream suprathermal protons.[129,130] These waves were shown to be oblique nonlinear compressional waves.[131,132]

The UCLA OGO-5 fluxgate magnetometer data were also used to study the heliographic latitude dependence of the dominant polarity of the solar wind,[133] the structure of shocks and discontinuities in the solar wind,[134-137] the dissipation at discontinuities and shocks,[138,139] and the spectrum of fluctuations of the interplanetary magnetic field.

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